APPLICATION OF WIND ENERGY TO GREAT PLAINS IRRIGATION PUMPING

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ABSTRACT

We investigated application of dedicated wind energy systems without energy storage for irrigation in the Great Plains. Major uses of irrigation energy were identified as pumping for surface distribution systems, which could be supplied by variable flow, and pumping for sprinkler systems using constant flow.

We developed a computer program to simulate operation of wind-powered irrigation wells. Pumping by wind turbine systems was simulated for two variable and two constant flow operational modes in which auxiliary motors were used in three of the modes. Using the simulation program, we made a comparison among the four modes of well yields and maximum pumping rates as a function of drawdown in a typical well.

The program also was used to determine monthly well yields using a 250 m^2 swept area wind turbine system in each mode if located at Columbus, Nebr.; Garden City, Kans.; and Amarillo, Tex. Irrigation required for various crops at these locations was then matched to monthly water yields. Such management practices as preplant irrigation, limited irrigation, or crop combinations were compared to determine how they affected the amount of annual capturable wind energy used. Last, we computed the percentage of fossil fuel replaceable by wind energy for the most efficient constant and variable flow modes of the wind powered systems.

We concluded that wind powered systems could supply half or more of the Great Plains irrigation energy demand using the present mix of sprinkler and surface distribution systems. However, in the variable flow modes that used little or no auxiliary energy, two wells would be required to yield amounts of water similar to a continuously pumped well.

Proper irrigation management is important to maximize wind energy use. Fully irrigated summer crops with preplant irrigation will use 30 to 60 percent of the annual, capturable wind energy, depending on crop and location. Fully irrigating equal areas of corn and winter wheat will use 70 to 85 percent of the wind energy, depending on location. With limited irrigation, 50 to 100 percent of the wind energy can be used, depending on practices followed.

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LIST OF SYMBOLS

C	Water used by corn (ha-cm)
CN	Number of windspeed cycles per month (mo^{-1})
C_p	Power coefficient of wind turbine
D_L	Well depth (m)
D_o	Saturated thickness of aquifer (m)
D_w	Height of water at well radius (m)
E	Specific yield of aquifer
H	Head at pump (m)
h_w	Height of water in well (m)
K	Hydraulic conductivity of aquifer (m/d)
m	Empirical function of τ
N	Pump rotational speed (rpm)
N_p	Pump efficiency
N_s	Specific speed of pump $[\frac{rpm}{ft^{3/4}}(\frac{gal}{min})^{1/2}]$
NIR	Crop net irrigation requirement (cm)
P	Wind turbine power (kW)
Q	Pumping rate or well discharge (m^3/s)
$(Q_{wt})_{max}$	Maximum pumping rate of wind turbine (m^3/s)
(Q_{ss})	Steady-state pumping rate (m^3/s)
R	Maximum radius of VAWT (m)
R_e	Radial distance from well where water table equals D_o (m)
R_t	Transmission ratio
R_w	"Effective" well radius (m)
SMC	Corn soil water stored (ha-cm)
SMW	Wheat soil water stored (ha-cm)
t	Time (d)
T_i	Windspeed cycle step
U	Windspeed (m/s)
VAWT	Vertical axis wind turbine
W	Water used by wheat (ha-cm)
WL	Well-loss coefficient (s^2/m^5)
WUE	Crop water use efficiency
λ	Wind turbine tip speed ratio
τ	Dimensionless time parameter
ω	Rotational speed of wind turbine (rad/s)

CONTENTS

Appendixes are not included in this report but are available upon request from the authors.

APPLICATION OF WIND ENERGY TO GREAT PLAINS IRRIGATION PUMPING[1]

Lawrence J. Hagen, Leon Lyles, and Edward L. Skidmore[2]

INTRODUCTION

The potential for applying wind power for irrigation pumping in the Great Plains becomes apparent by comparing wind power distribution (fig. 1) and major irrigation aquifers (fig. 2).

A region of high wind power extends northward from northern Texas in which average annual wind power exceeds 300 watts/m². In portions of the area, average power exceeds 500 watts/m². The Ogallala aquifer also extends from northern Texas to the South Dakota border and supplies a major portion of the irrigation water in the Great Plains. Thus, both the wind power and power demand are present, but it must be determined to what extent this use of wind power will be constrained by technical characteristics of irrigation systems and irrigated crops.

OBJECTIVES

In this investigation we identified applications for wind energy systems without energy storage in Great Plains irrigation schemes and determined some of the irrigation-management and engineering problems associated with the chosen applications. Specific objectives of the investigation included:

1. To survey the irrigation methods, crops, fuels (energy), lifts, and water pumped in the Great Plains and to determine the operational modes of wind turbines needed if large amounts of fossil fuels are to be replaced by wind energy.
2. To develop a general procedure to calculate effects of wind turbine size, rated windspeed, and operational mode on resultant well yield and drawdown for a given aquifer and wind regime.
3. To determine which crop combinations and management practices permit maximum use of wind energy to pump irrigation water.
4. To determine how much fossil fuel could be saved by using wind power in Great Plains irrigation.

PROCEDURE

To accomplish objective one, we reviewed the literature on irrigation in the Great Plains. Much of the necessary data has been compiled by Sloggett (*21*)[3] and the editors of the *Irrigation Journal* (*9*). Calculations from their data were made to determine where large amounts of wind energy could be used in Great Plains irrigation.

We accomplished objective two by first determining realistic modes of operation for a wind turbine coupled to a turbine pump. Next, we formulated approximate equations that described the behavior of a water table aquifer under cyclic pumping, and finally, we developed a computer program to solve those equations for complex cyclic inputs of wind power. We calculated reduction in well yield by various modes of wind turbine operation by using the computer program.

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[3] Italic numbers in parentheses refer to Literature Cited, page 19.

Figure 1.—Mean annual wind power (watts/m²) estimated at 50 m above exposed areas. Over mountainous regions (shaded areas), the estimates are lower limits expected for exposed mountain tops and ridges (*4*).

The third objective we accomplished by matching the irrigation requirements of various crop combinations to stored soil water and calculated well yield on a monthly basis. Management practices were determined that would use wind energy most efficiently.

We accomplished the final objective by calculating the percentage of wind energy that could be used to power sprinkler and surface distribution irrigation systems using appropriate modes of wind turbine operation.

APPLICATIONS FOR WIND ENERGY IN GREAT PLAINS IRRIGATION

Total 1975 irrigated acreage in the United States was estimated to be 21,989,451 ha, with slightly more than 50 percent of that acreage in the 10 Great Plains States. Sloggett (*21*) estimated that in 1974 more than 14 million ha in this country were irrigated with the aid of energy-using pumps on farms and ranches; about 8 million ha of those were in the Great Plains. While irrigated acreage in some states, such as Texas, may decline in a few years because of dropping water tables, in others, such as Nebraska, continued rapid expansion of irrigated acreage is expected. Thus, a large and continuing energy source is needed to power farm irrigation pumps in the Great Plains.

In 1974, Sloggett (*21*) estimated that irrigation pumping consumed 20 percent of U.S. energy used for on-farm production and totaled 7.66 x 10^{10} kWh. About 66 percent of that total was used in the Great Plains where nearly 70 percent of the energy is used for lifting groundwater; about 25 percent is used by sprinklers (table 1).

The two major types of distribution systems shown in table 1, sprinkler systems and surface systems, place different operating restraints on the pumping unit used. Sprinkler systems are usually designed for constant flow and nearly continuous operation during peak water-use periods. They are recommended for fields with a high or variable infiltration rate, low water-holding capacity, or rolling topography. Because sprinklers save labor, they also are applied on many other fields and are used on

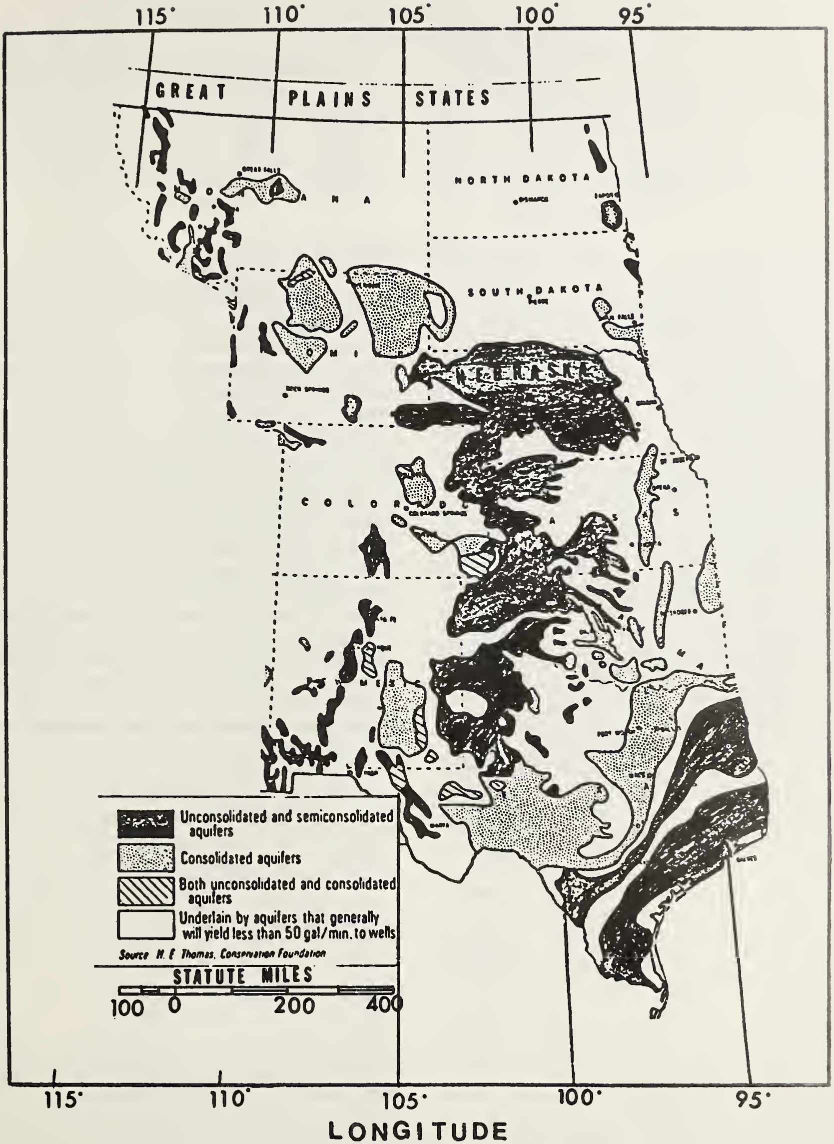


Figure 2.—Major groundwater aquifers in the Great Plains (5).

TABLE 1.—*Energy used to lift and distribute irrigation water on farms in the Great Plains States*[1]

Region	Pumping: Ground water	Pumping: Surface water	Distribution system: Sprinkler	Distribution system: Surface	Distribution system: Total
	Billion kWh	*Billion kWh*	*Billion kWh*	*Billion kWh*	*Billion kWh*
Great Plains	35.10	1.07	12.58	1.88	50.63
Percent	69.3	2.1	24.9	3.7	100.0

[1] See Literature Cited (*21*).

about 28 percent of the irrigated area in the Great Plains. To supply power to produce a steady output from sprinkler systems, wind turbines must be coupled to auxiliary power sources. The water likely would be pumped as used by the sprinkler, so about 20 percent of the total (28 percent of the pumping energy) would be used to lift and 25 percent used to pressure water for sprinklers. Thus, if wind powered, about 45 percent of the total energy consumed would be used by sprinkler systems requiring auxiliary power sources.

The remaining 55 percent of the energy is used for pumping water into surface distribution systems. This energy could be supplied by wind turbines and auxiliary power sources from which the flow would be allowed to vary. Small reservoirs or large canals could be used to store water temporarily for such surface distribution systems to buffer short-term variations in flow to permit efficient irrigation.

Nebraska, Kansas, and Texas contain 80 percent of the Great Plains irrigated acreage. Water can be pumped all months of the year in Texas and from 9 to 11 months in Kansas and Nebraska. Pumping time varies widely from farm to farm and somewhat between years, depending on precipitation. Anschutz and Lipper (*1*) reported county averages of operating time for electric pumps to be about 1,000 hours (11 to 12 percent of the year) in western Kansas. Increasing irrigated areas and decreasing water tables are causing many farmers to extend their pumping time each year, particularly in dry years. New (*16*) reported that, in 1974, many pumps in Texas were operated nearly continuously from February through August, or about 5,000 hours. The average lift for groundwater decreases from south to north and ranges from 107 to 21 m (Appendix A).

We must consider also the kind of fuel wind turbines might replace in pumping water. Table 2 shows that natural gas is used to supply water for more than 50 percent of the irrigated acreage in the Great Plains. The largest amounts of natural gas are used in Texas, Nebraska, Kansas, and New Mexico. When natural gas supplies become limited in the future, wind power might supply a replacement for natural gas in Great Plains irrigation. Out-

TABLE 2.—*Fuels used on farms for irrigation in Great Plains States.*[1]

Energy source	Distribution systems: Surface	Distribution systems: Sprinkler	Percent by fuel
	1,000 ha	*1,000 ha*	
Electricity	1,557.43	605.68	27.0
Diesel	552.46	214.84	9.6
Gasoline	95.57	37.21	1.7
Natural gas	2,911.54	1,132.29	50.5
LPG	648.48	252.17	11.2
Total	5,765.48	2,242.19	
Percent of U.S.	57.1	54.6	
Total U.S.	10,090.0	4,104.70	

[1] See Literature Cited (*20*).

TABLE 3.—*Crop areas irrigated in Great Plains States*[1]

State and region	Corn	Sorghum	Hay and pasture[2]	Small grains	Cotton	Other
	1,000 ha	*1,000 ha*	*1,000 ha*	*1,000 ha*	*1,000 ha*	*1,000 ha*
North Dakota	19.0	0	18.2	6.1	0	11.4
South Dakota	72.9	3.2	60.7	8.5	0	6.4
Nebraska	2,174.8	80.9	344.0	40.5	0	199.0
Kansas	657.6	210.4	141.6	224.6	0	43.5
Oklahoma	50.0	74.9	75.8	102.0	35.2	47.0
Texas	647.5	971.3	182.1	728.5	768.9	256.6
Montana	0	0	1,054.9	135.9	0	28.8
Wyoming	64.8	0	466.7	101.2	0	38.7
Colorado	360.2	35.6	624.4	109.3	0	108.5
New Mexico	0	50.1	153.8	72.4	30.0	8.5
Totals	4,406.8	1,426.4	3,122.2	1,529.0	834.1	748.4
Percent	36.5	11.8	25.9	12.7	6.9	6.2

[1] See Literature Cited (*9*).
[2] Includes alfalfa.

side the Great Plains, electricity is the dominant power source.

Finally, in adapting new systems, we must consider the crops that are irrigated. Table 3 shows that corn is the most popular crop, and it is usually fully irrigated. Large acreages of sorghum and wheat also are irrigated, but these crops can be grown under partial irrigation. Cotton is limited to the southern portion of the Great Plains, while some irrigated alfalfa is grown in every state. Among the crops in the "other" category are sugar beets, potatoes, popcorn, soybeans, peanuts, vegetables, and fruits. Total irrigated area in table 3 exceeds 12 million ha. This area exceeds that in table 2 because it includes areas irrigated by water not pumped on farms as well as increases in irrigated area with time.

WIND ENERGY AND WELL YIELD

Modes of Operation

In designing an irrigation system to use wind power, one must supply power for a variable or constant flow mode. Gilmore, Barieau, and Nelson (*6*) discussed the problems of wind-powered irrigation using positive displacement and airlift pumps coupled to horizontal axis rotors. Here, we compare modes of operation for a wind turbine mechanically coupled to a deep-well vertical turbine pump of conventional design. The specific wind turbine used for this analyses was a Darrieus vertical axis wind turbine (VAWT) because it was the only commercial wind turbine available with mechanical power output at the time of this study. Thus, it most likely represented the type of wind turbine to be used for irrigation experiments in the near future.

To compare modes, the following information is needed for the range of operating conditions: (a) pump efficiency, (b) wind turbine power coefficient, (c) transmission efficiency, and (d) wind energy distribution at a location.

Deep-well turbine pumps used for on-farm irrigation pumping have moderate specific speeds (N_s) that range from about 1,500 to 5,000. N_s is the similarity criterion for turbine pumps and determines many important dimensions of the pump. It is defined at the pump's best efficiency point as:

$$N_s = N\sqrt{Q}/H^{.75}$$

where the units N in rpm, Q in gal/min, and H in feet of head are used in U.S. practice (*12*).

Figure 3 shows behavior of a typical turbine pump if operated at variable speed with a constant head or a head that increases linearly with output. The maximum rpm range has a ratio of final to initial operations rpm of about 1.8. At lower than 1,160 rpm, shutoff head would likely be encountered in most applications, while above 2,060 rpm, problems with critical shaft speeds and cavitation may be encountered in usual designs. (For a discussion of these latter problems, see Stepanoff (*23*).) Lines of constant efficiency also denote lines of constant N_s. This fact was used to estimate pump performance at 2,060 rpm, while the performance at lower speeds was obtained from the manufacturer's test results. We used the operational line of increasing head with output from figure 3 in our calculations. Pumps with low N_s differ slightly, as illustrated in figure 4.

Results of wind-tunnel tests reported by Sandia personnel, who used a small Darrieus VAWT of 0.13 solidity, are shown in figure 5 (*3*). Because performance improves with increasing blade Reynolds number, these results are predicted to be conservative for large VAWT (*25*). However, effects of atmospheric turbulence and support struts tend to reduce the performance of large machines. Thus, for our calculations the test results in figure 5 were used unchanged. Finally, we assumed the efficiency of constant-ratio or variable-ratio speed increasing transmissions used in the various modes to be 90 percent.

Many ways of using wind power for irrigation pumping can be readily conceived. However, those that are most feasible will be those that best exploit (or cause least conflict among) the known characteristics of wind turbines, deep-well pumps, wells, irrigation distribution systems, and infiltration of water into the soil. In addition, because wind power systems are capital intensive in themselves, it is assumed that wind power irrigation schemes that require a minimum of other capital investment, that is, additional wells, battery storage units, large water storage reservoirs, are more likely to be

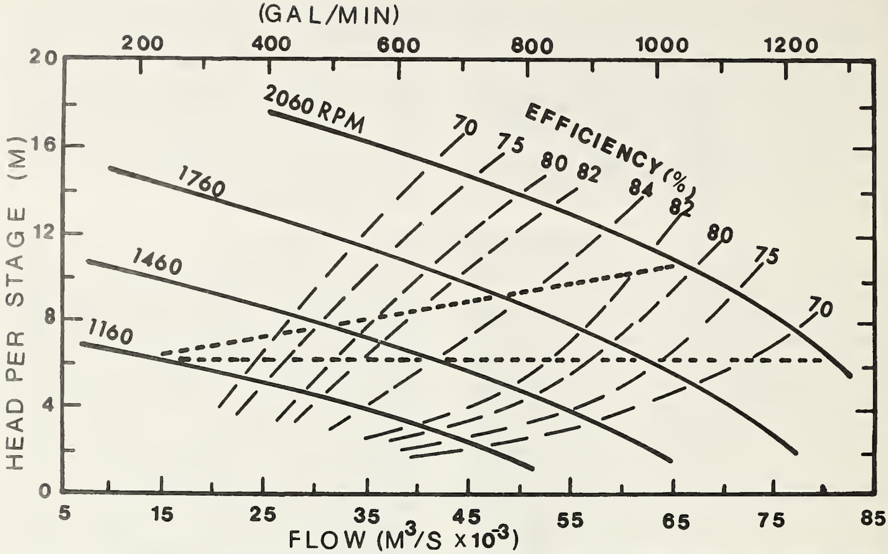


Figure 3.—Pump performance curves for a vertical turbine pump with N_s of 4,000. Dashed lines (---) indicate possible operational behavior at various speeds with a fixed and a linearly increasing head.

feasible. These factors led us to narrowing the many possibilities to the following four modes of wind turbine operation for specific consideration.

Mode 1: In this mode, the wind turbine drives the turbine pump through an overrunning clutch using a fixed-ratio transmission system. The turbine pump is also driven by a speed-governed auxiliary power source having a capacity equal to that of the rated power of the wind turbine. The constant speed pump operation would be suitable for use with a sprinkler distribution system. Because of the fixed transmission ratio and the constant pump speed, the wind turbine will operate at a constant rotational velocity when the wind is blowing, regardless of the windspeed. The overall efficiency (wind-to-water) for this mode of operation can be calculated using estimates of pump efficiency (80 percent) and permitting the coefficient of performance (C_p) of the wind turbine to vary with the windspeed. The result is shown in figure 6. It can be seen that as windspeed is reduced, the constant speed wind turbine operates at a tip speed ratio, which increases well beyond the optimum. This reduces the power coefficient of the wind turbine and greatly reduces the power produced at low windspeeds.

Mode 2: This mode of operation is identical to Mode 1 with the exception that a variable-speed transmission system is used at low windspeeds, permitting the wind turbine to slow down at low windspeeds to maintain a tip speed ratio, which maximizes the power coefficient. The performance of this system is also shown in figure 6.

Mode 3: In this mode, the wind turbine is coupled to the pump with a constant-ratio transmission, with no auxiliary power source. By properly matching the size of the pump to the size of the wind turbine, the wind turbine will tend to operate at a speed that is proportional to the windspeed, since it will produce power proportional to the cube of its rotational speed, and it is driving a turbine pump whose power demand is proportional to the cube of its rotational speed. However, the efficiency of the pump will vary with rotational speed, with lowest efficiencies occurring at the lowest and

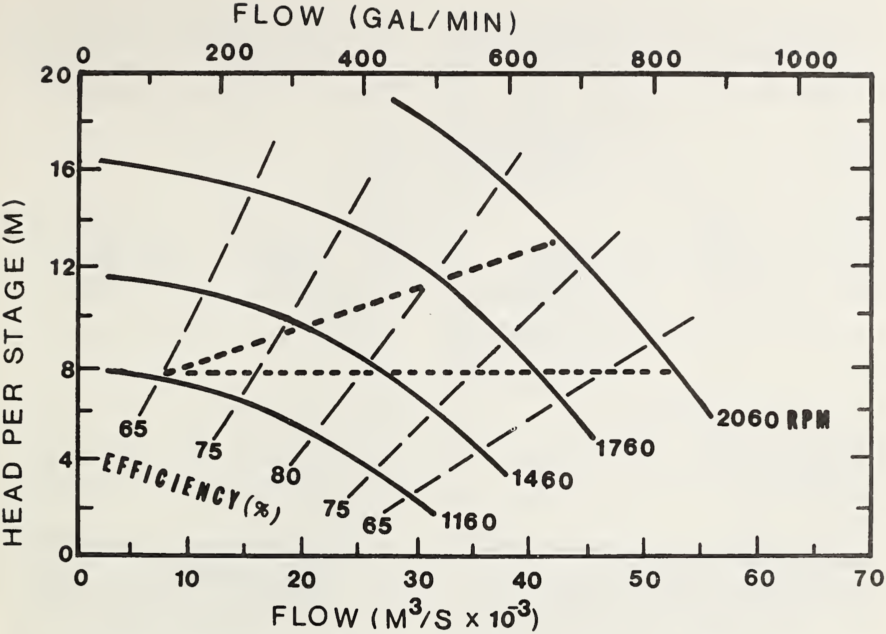


Figure 4.—Pump performance curves for a vertical turbine pump with N_s of 2,500. Dashed lines (---) indicate possible operational behavior at a fixed and a linearly increasing head.

highest rotational speeds. Using published data on pump efficiency (fig. 3) and assuming

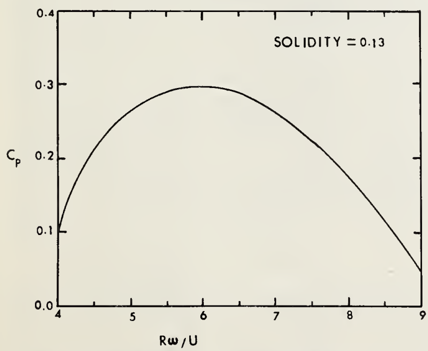


Figure 5.—Average power coefficient (C_p) data as a function of tip speed ratio (Rω/U) for a Darrieus VAWT with NACA 0012 blades (*3*).

constant C_p of the wind turbine of 0.29, the overall efficiency of mode 3 operation can be calculated, as shown in figure 7. Maximum rotational speed is assumed to occur at 11 m/s, and an overspeed control device would be necessary to prevent higher rotational speeds when windspeeds exceed 11 m/s.

Mode 4: This mode of operation uses a small auxiliary power source to supplement the wind turbine at low windspeeds and uses a variable-ratio transmission between the wind turbine and pump. For our analysis, we chose an auxiliary power source sized to equal 40 percent of the rated wind turbine power. This size keeps the speed of the pump high enough so that it operates near maximum efficiency at low windspeeds. Performance and operational characteristics for such a system were computed and are shown in figure 7. The motor and variable-ratio transmission reduce the pump speed range, which may reduce the number of pump stages needed.

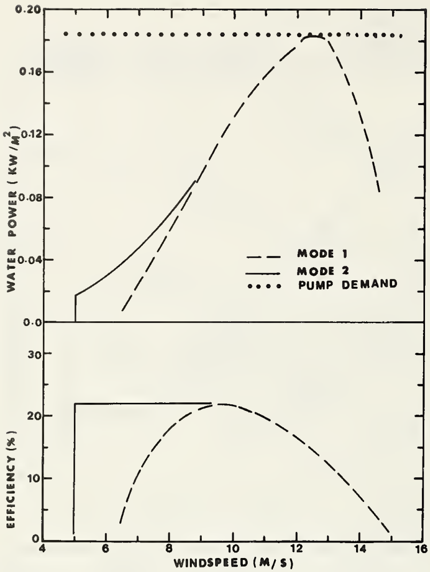


Figure 6.—Overall efficiency and water power of a wind turbine and pump in modes 1 and 2.

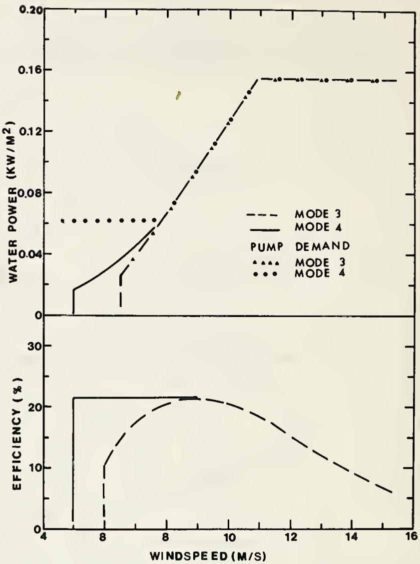


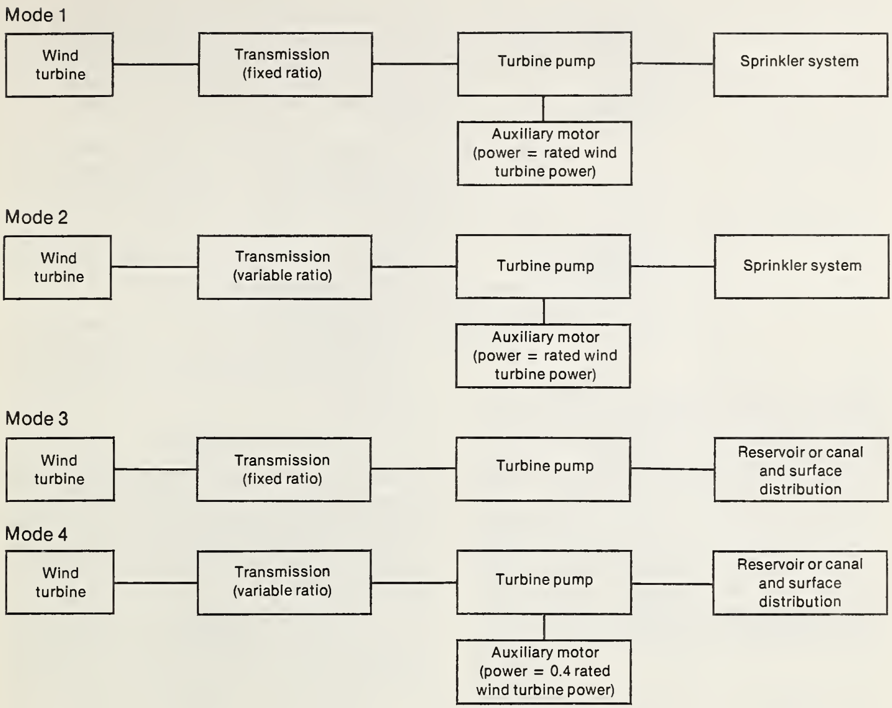
Figure 7.—Overall efficiency and water power of a wind turbine and pump in modes 3 and 4.

Major characteristics of the four modes are summarized in table 4, while the major system components are shown in block diagram form on the opposite page.

The overall efficiency curves can be moved right or left by changing the transmission gear ratio and pump size or wind turbine size. However, to maximize useful work from the

TABLE 4.—*Major characteristics of operation modes*

Characteristic	Mode 1	Mode 2	Mode 3	Mode 4
Configuration:				
Wind turbine to pump transmission ratio	Fixed (R_t = constant)	Variable ($R_t \propto 1/U$)	Fixed (R_t = constant)	Variable $U > U_c$, R_t = constant $U < U_c$, $R_t \propto 1/U$
Auxiliary motor power	1.0 × wind turbine rating	1.0 × wind turbine rating	None	0.4 × wind turbine rating
Irrigation distribution system suitability	Sprinkler or surface flow	Sprinkler or surface flow	Surface flow	Surface flow
Operation:				
Pump speed	Constant	Constant	Variable	Variable at high wind Constant at low wind
Well discharge	Constant	Constant	Variable	Variable
Pump efficiency	Constant	Constant	f(U)	f(U)
Wind turbine speed	Constant	$\omega \propto U$	$\omega \propto U$	$\omega \propto U$
Wind turbine tip speed ratio	$\lambda \propto 1/U$	λ = constant	λ = constant	λ = constant
Wind turbine power coefficient	f(U)	Constant	Constant	Constant



VAWT, maximum efficiencies should coincide with windspeeds where maximum wind energy occurs (fig. 8).

We calculated the wind energy here and in other parts of this study as follows: a monthly Weibull distribution (Appendix B) (*2, 11*) was calculated from the windspeed summaries reported by Reed (*17*). The windspeed measurements were assumed to be from the 10-m height, while the probable center height of a wind turbine is estimated to be 20 m. The windspeeds at 20 m were estimated as

$$U_{20} = U_{10}(2)^{1/7}.$$

Finally, the wind energy (P_i) at the midpoint of each 1-m/s windspeed group was calculated as

$$P_i = 6{,}125 \times 10^{-7} U_i^3(\Delta t_i)$$

where P_i is kWh/m² per mo, U_i is m/s, and Δt_i is h/mo in the ith windspeed group using an average month of 730 h. Energy distributions from locations representing high, medium, and low windspeeds during July were calculated (fig. 8).

The product of wind energy and efficiency was integrated over all windspeeds to determine monthly energy from the VAWT in the four modes (fig. 9). Mode 3 extracts 5 to 10 percent more energy than does mode 1; using variable-ratio transmissions (modes 2 and 4) increases useful energy 10 to 25 percent.

Response of Water-Table Aquifer to Complex Pumping Cycles

Understanding the behavior of the aquifer under complex pumping cycles is necessary to determine both the well-drawdown and yield of irrigation water a wind-powered irrigation pump might produce. Several approaches to the problem are possible. Transient aquifer behavior

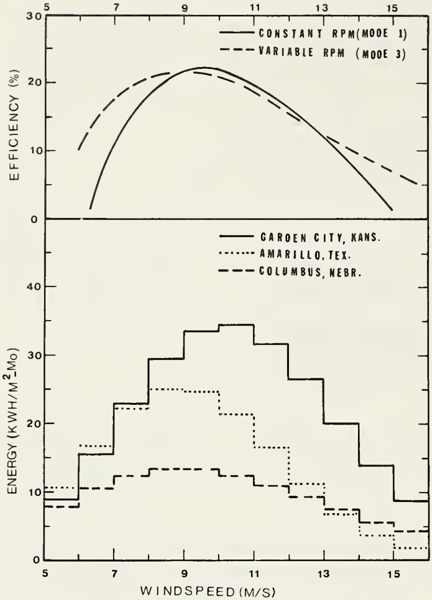


Figure 8.—Overall efficiency and wind energy as a function of average 20 m July windspeeds at three locations.

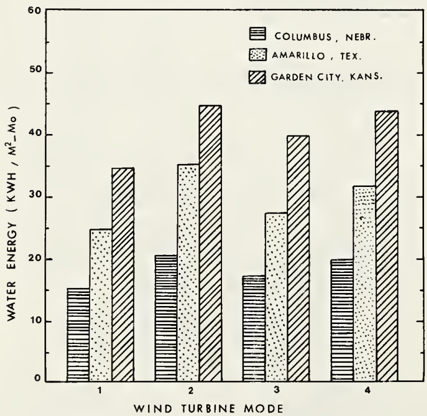


Figure 9.—July water energy from wind as a function of VAWT operational mode at Garden City, Kans.; Amarillo, Tex.; and Columbus, Nebr., for a 0.13 solidity Darrieus VAWT and vertical turbine pump with N_S = 4,000.

can be described by differential equations and the equations solved by finite difference methods (*14*). When complex pumping cycles are imposed as part of the problem, however, long computing times are necessary to reach a solution.

We used a relatively simple model of the pumping cycles and water table response in this study. Equations in the model are outlined here, and the computer program to solve the equations is listed in Appendix C. The model applies only to horizontal, nonleaky, water-table aquifers, but these represent most of the Great Plains aquifers used for irrigation.

Useful, approximate solutions to the differential equations of drawdown were reported by Hantush (*8*). The solutions are for $\tau < 5$ and for $\tau > 5$, where τ is a dimensionless time factor of the form

$$\tau = (Kt/ED_o) \qquad [1]$$

where K is hydraulic conductivity (m/d), t is time since discharge of well began (days), E is specific yield (dimensionless), and D_o is saturated thickness of aquifer (m) (fig. 10).

For $\tau < 5$, Hantush (*8*) reported drawdown is approximately

$$D_o - D_w = (Q/2\pi KD_o)\,[m + \ln(D_o/R_w)] \qquad [2]$$

where m is a function of τ and given by the empirical relation

$$m = -0.1 + 4.628(\tau) - 4.014(\tau^{1.05}). \qquad [3]$$

Q is well discharge, R_w is "effective" well radius, and D_w is height of water at the well radius.

For the case of $\tau > 5$, the aquifer response is approximated as

$$D_o^2 - D_w^2 = \frac{Q}{\pi K} \ln(1.5\, D_o \sqrt{\tau}/R_w). \qquad [4]$$

Equations 2 and 4 apply only to wells that completely penetrate the aquifer and neglect drawdown from well losses. Near $\tau = 5$, a weighted average of equations 2 and 4 was used to calculate the drawdown.

Hantush (*8*) also noted that water levels at any time after pumping ceases can be obtained by adding the effects of a well recharging at rate Q from the time pumping ceases to the effects of a well continuously discharging at rate Q from the time pumping begins. Thus, we can add the drawdown caused by previous cycles to

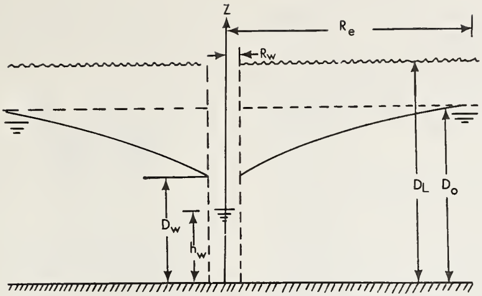


Figure 10.—Diagram of a horizontal water-table aquifer showing notation used in text.

the drawdown caused by the current pumping cycle.

To illustrate the solution obtained from equations 2 and 4, we calculated the behavior of a typical large irrigation well for 6-d cycles (3 d on and 3 d off) at constant Q, compared with the same well continuously pumped (fig. 11). Maximum drawdown and average head were less, and total yield was half in the cycled well compared with the continuous well. Of course, for equal total water yields, the least energy is required if the well is pumped continuously. Reducing the fraction of pumping time also reduces the maximum drawdown (fig. 12).

The cyclic drawdown is composed of two parts—the drawdown caused by current Q and the residual from previous cycles. After 30 d (fig. 11), the residual causes 7 percent and the current Q about 30 of the aquifer to be dewatered. The residual drawdown is small, but exact computation from equations 2 and 4 requires a large number of computer iterations, unless the cycles have constant Q, as in our example. Thus, to simplify calculations, the residual was calculated as the drawdown caused by a well pumping at Q averaged over the preceding cycles plus a well recharging at average Q from the beginning of the current "on" period.

To this point, we have considered regular cycles with constant Q. A wind turbine produces a series of power levels, however, and the Q and drawdown must vary to absorb the in-

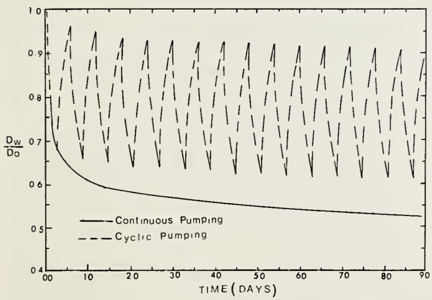


Figure 11.—Relative water levels at a well in a water-table aquifer pumped continuously and in 6-d cycles (3 d on and 3 d off). Aquifer and well characteristics were K = 18.3 m/d, D_o = 45.7 m, R_w = 30.5 cm, E = 0.2, and Q = 0.126 m³/s (2,000 gal/min). Later computer simulations were performed using somewhat different characteristics but chosen to give similar water level behavior.

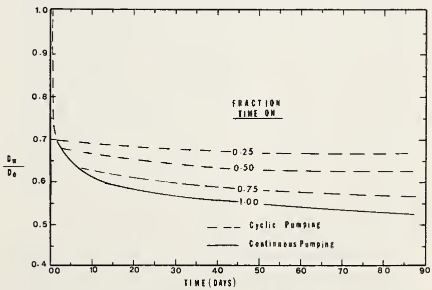


Figure 12.—Minimum water levels at a water-table aquifer well pumped continuously and in 6-d cycles with various fractions of time on. Aquifer and well characteristics same as figure 11.

put power levels. Now the well discharge $Q(m^3/s)$ at power level P (kW) is

$$Q[(D_L - D_w) + WL(Q^2)] = PN_p/9.806 \qquad [5]$$

where N_p is pump efficiency, WL is well loss coefficient (s^2/m^5), and other quantities are identified in figure 10.

Well loss is defined as the drawdown in a discharging well caused by the turbulent flow of water into and inside the well (the difference between D_w and h_w in fig. 10). According to Reinke and Kill (*18*), well loss should account for 20 percent or less of the total drawdown in properly designed wells. Thus, it is a significant factor and should be included in determining well discharge. Jacob (*10*) suggested well loss could be described as a constant times the square of the discharge rate, and we have adopted this suggestion in equation 5. Rorabaugh (*19*) gave a slightly different form for well loss, but his results generally agree with those of Jacob.

Equations 1 through 5 can be used in an iterative procedure to determine maximum drawdown and yield in a well with complex cycles of power input as follows: for a given power input, estimate Q and calculate a residual and current drawdown using equations 1 to 4. Check the results in equation 5 to see if the available power is matched. If not, adjust Q and calculate a new drawdown. Continue iteration until drawdown and Q match the power input for each step of the cycle.

Modeling Cyclic Power Input

In the preceding section, we presented the equations to determine well yield and drawdown from arbitrary power inputs. The duration and magnitude of the power outputs from a wind turbine can be obtained in two ways: (a) use actual serial windspeed records, or (b) use monthly summaries of windspeed distribution and assume some "model" of the windspeed cycles during the month. Because summarized distributions are readily available and easily described using the Weibull distribution, we used the latter procedure.

A plausible model of a wind-powered system is an arbitrary number of cycles per month (CN) with each cycle consisting of a number of constant-power steps (fig. 13). The number of steps depends on the windspeed increments desired (1-m/s increments are a reasonable

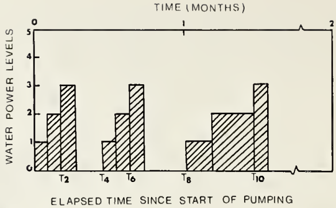


Figure 13.—Schematic of monthly pumping cycles. Zero power level represents time windspeeds were less than wind turbine cut-in windspeeds, while width of other steps represents duration of various power (windspeed) levels.

choice), and the cut-in, rated, and cut-out windspeeds selected for the wind turbine. The duration of each step is the monthly windspeed duration at each speed increment divided by CN. The power level of each step depends on the windspeed and size and efficiency of wind turbine, pump, and transmission.

Modeling the windspeed distribution as a series of constant length cycles permits exact values of total energy, power levels, and total duration to be used. The model does not use a range of durations for the cycles, however, as found in the serial windspeed record. This feature could be easily incorporated, if reliable statistics were available, to describe the range of durations of windspeed cycles.

Large-scale weather systems generally cause 5 to 10 major wind periods per month. In addition, a diurnal wind pattern is imposed upon the major weather systems. Thus, calculations from serial windspeed records show a range of durations for each windspeed (fig. 14). At Garden City, Kans., the windspeed exceeded 6 m/s about 60 times during the month, but duration rarely exceeded 24 h. Windspeeds of 10 and 12 m/s were exceeded only 33 and 9 times, respectively. Thus, one might choose a range of about 10 cycles for high and 60 cycles for low windspeeds. Drawdown varies slowly with pumping time, particularly at low windspeeds, so the number of cycles is not very critical (fig. 15). To predict maximum drawdowns caused by high windspeeds, 10 CN were used in our calculations.

Well Performance

The total yield and maximum pumping rate of a well must be considered in designing wind-

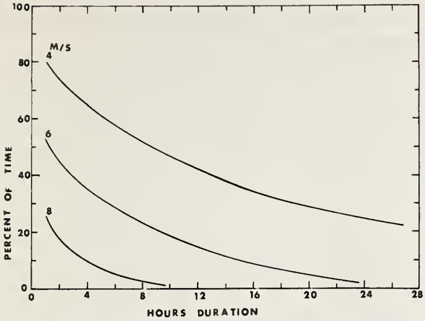


Figure 14.—Percentage of time when windspeeds remained equal or greater than a given windspeed for a successive number of hours (July 1977, Garden City, Kans.)

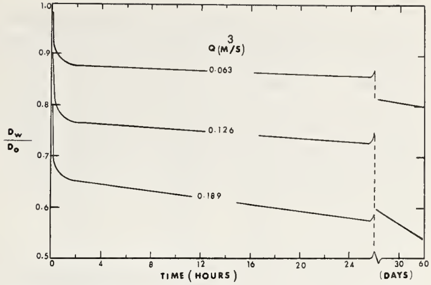


Figure 15.—Relative water levels at a well in a water-table aquifer pumped continuously at three rates shown. Aquifer and well characteristics were K = 18.3 m/d, D_o = 45.7 m, E = 0.20, and R_w = 30.5 cm.

powered irrigation systems. The model described in previous sections was used to determine the performance of a typical irrigation well at Garden City, Kans., using four operational modes of the wind turbine (table 5). Steady-state (ss) operation of the well was considered as a drawdown of 18 m (60 percent) after 60 d of continuous pumping at 0.063 m³/s (≃ 1,000 gal/min). Well loss accounted for 18 percent of the ss drawdown. A range of wind turbine sizes was used to create unsteady well drawdowns of 45 to 75 percent of the saturated thickness (D_o).

When the wind-powered well reached 60 percent drawdown, the maximum Q to the well exceeded the steady-state Q by 23 to 33 percent, depending on operational mode (fig. 16). The

TABLE 5.—*Specifications for calculating drawdown, maximum pumping rate, and yield of well*

Variable	Units	Value	VAWT mode
Aquifer:			
Hydraulic conductivity (K)	m/d	20.0	1-4
Specific yield (E)	dimensionless	.20	1-4
Well:			
Well depth (D_L)	m	70.0	1-4
Saturated thickness (D_o)	m	30.0	1-4
Well loss coefficient (WL)	s²/m⁵	800.0	1-4
Effective well radius (R_w)	m	.3	1-4
Pump and transmission:			
Efficiency (N_p)	decimal fraction	.72	1, 2
		variable	3, 4
Wind turbine:			
Cut-in windspeed	m/s	5.0	2, 4
		6.0	1, 3
Rated windspeed	m/s	11.0	3, 4
		15.0	1, 2
Cut-out windspeed	m/s	15.0	1-4
Efficiency	decimal fraction	.3	3, 4
		variable	1, 2
Height above surface	m	20.0	

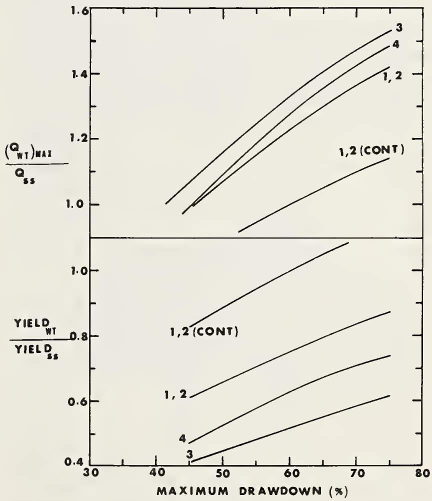


Figure 16.—Variation in maximum inflow and total well yield as a function of maximum drawdown for modes 1 to 4 and various sizes of VAWT at Garden City, Kans., for average of spring and summer windspeeds. Steady state (ss) operation was defined as a drawdown of 60 percent with continuous pumping.

upper limits of safe inflow to a well are dictated by well-screen areas, packing, and aquifer characteristics (*18*). Thus, special attention is necessary in well development to insure maximum yields of a wind-powered system. Somewhat larger diameter wells with improved packing would permit increased flow rates, and their economics should be considered if new wells are developed specifically for wind-powered irrigation.

At 60 percent drawdown, the wind-powered well yielded 50 to 75 percent of total water volume of the ss well when auxiliary power sources were not operated below cut-in windspeed in modes 1, 2, and 4 (fig. 16). The lines marked continuous in modes 1 and 2 occurred when auxiliary power was used below cut-in windspeed.

At locations where windspeeds are lower than at Garden City, well yield also will be lower. At these locations, an increase of wind turbine size and decrease in rated windspeed can be used to increase yields while maintaining Q the same as at Garden City. It is clear, however, that in modes 3 and 4 two wind-powered wells would be needed to replace the yield from a single, continuously pumped well. In modes 1 and 2, the auxiliary power source is large and can be operated when windspeed is below cut-in to equal the ss output if needed in peak water-use periods. If mode 1 or 2 is used to power sprinklers, then continuous operation is likely, and a second well would be unnecessary.

MATCHING CROP WATER NEEDS AND WIND ENERGY

For economic reasons, a wind turbine should be used as much of the year as possible. Here, we assumed that the wind turbine was large, relative to farm-energy needs other than pumping, and was dedicated to irrigation pumping alone. Thus, it was necessary to determine irrigation management practices and operational modes that would maximize the annual operating time and also replace a high percentage of fossil fuels currently used for pumping.

Calculations were made for turbines at Amarillo, Tex.; Garden City, Kans.; and Columbus, Nebr., as follows: First, we calculated monthly water yields from the well described in table 5 for 1 year using four modes of operation of a 250 m² wind turbine and the windspeed distribution for each location (fig. 17). The wind turbine size was chosen to provide maximum well yield without dewatering the aquifer, which would cause a shutdown during maximum pumping periods. The calculated maximum drawdowns ranged from 48 to 78 percent of the saturated thickness during various months. In modes 1, 2, and 4, the auxiliary motor was used to operate the pump continuously in July and August. Second, we matched the monthly water yields to the net irrigation requirements (NIR) (table 6) by using various irrigation management practices. Finally, the annual percentage of capturable wind energy used for irrigation and the percentage of fossil fuels replaced in each mode were calculated. (Note that using NIR rather than actual irrigation application

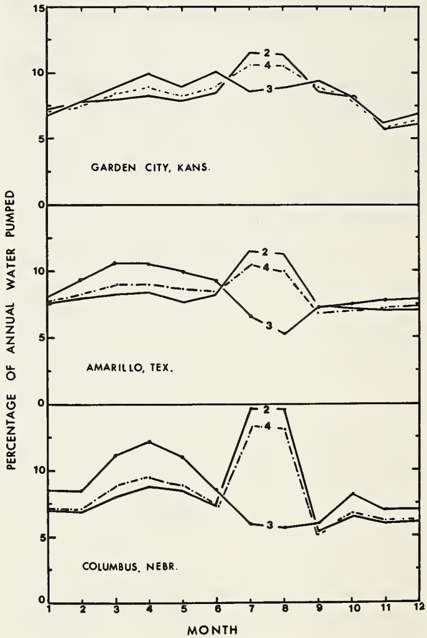


Figure 17.—Monthly percentage of annual water pumped at Garden City, Kans.; Amarillo, Tex.; and Columbus, Nebr., for well of table 5 and VAWT in operational modes 2, 4 (continuous in July and August), and mode 3.

TABLE 6.—*Monthly net irrigation required (cm)*[1] for fully irrigated crops in eastern Nebraska (A)[2], southwest Kansas (B)[3], and Texas High Plains (C)[4]

	Crop										
	Corn			Sorghum			Alfalfa			Wheat	
	Areas										
Month	A	B	C	A	B	C	A	B	C	B	C
Jan									1.5		1.0
Feb									3.0		4.3
March									9.1		12.5
April							0.6	0.7	10.7	7.1	15.2
May							5.1	8.4	15.0	10.9	12.5
June	1.7	7.1	9.3	1.1	0.1	0	10.2	13.1	19.3	1.4	4.1
July	13.4	17.4	21.2	14.3	15.4	9.7	16.7	16.3	18.0		
Aug	13.9	16.4	20.9	12.2	15.7	18.9	13.6	14.4	10.9		
Sept	7.6	5.3		4.5	3.9	9.1	7.4	8.7	12.9	1.9	
Oct	1.5							3.4	8.1	8.2	
Nov									4.6	1.5	2.3
Dec									1.0		.8
Totals	38.1	46.2	51.4	32.1	35.1	37.7	53.6	65.0	114.1	31.0	52.7

[1] See Literature Cited (*9*).
[2] See Literature Cited (*26*).
[3] See Literature Cited (*27*).
[4] See Literature Cited (*13*).

does not affect the results as long as the irrigation efficiency remains nearly constant throughout the season.)

For fully irrigated crops, two management practices—preplant irrigation and crop combinations—were considered. Preplant irrigation is widely practiced in Great Plains areas where precipitation does not usually fill the soil profile between crops. Most irrigated soils can store 20 cm or more of water in a 1.5-m profile, and only the shallow, coarse-textured, or clay soils store less (table 7). Of course, not all the water can be withdrawn from the profile before irrigation is needed; we assumed 12 cm (about 60 percent depletion) as maximum allowed in the calculations.

Many irrigators also grow a combination of crops to spread farm workload and reduce risks. For example, averaging irrigated areas of Texas, Oklahoma, and Kansas shows about 2.5 ha of corn and grain sorghum for each hectare

TABLE 7.—*Average available water capacity for Kansas soils*[1]

	0-30 cm soil layer			30-152 cm soil layer		
Soil texture	Field capacity	Wilting point	Available water content	Field capacity	Wilting point	Available water content
	cm/cm	*cm/cm*	*cm/cm*	*cm/cm*	*cm/cm*	*cm/cm*
Sand	0.14	0.06	0.08	0.12	0.05	0.07
Loamy sand	.19	.07	.12	.17	.07	.10
Sandy loam	.24	.09	.15	.22	.09	.13
Fine sandy loam	.29	.11	.18	.29	.13	.16
Loam	.34	.13	.21	.35	.16	.19
Silt loam	.38	.15	.23	.40	.19	.21
Silty clay loam	.39	.18	.21	.40	.21	.19
Sandy clay loam	.38	.19	.19	.39	.22	.17
Clay loam	.38	.21	.17	.39	.24	.15
Silty clay	.37	.23	.14	.39	.26	.13
Clay	.37	.25	.12	.39	.28	.11

[1] See Literature Cited (*27*).

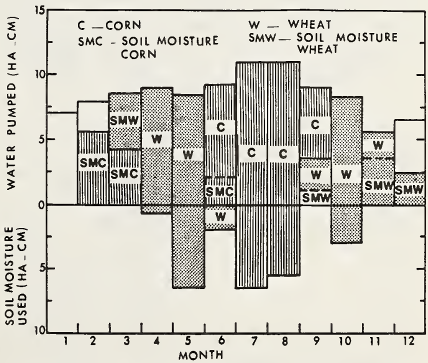


Figure 18.—Annual water allocation from pumping and soil moisture to meet the NIR of 1 ha of corn and 1.36 ha of winter wheat at Garden City, Kans., using a wind turbine pumping in mode 4 operating continuously in July and August.

of small grains; the latter are principally winter wheats (table 3).

Figure 18 illustrates how the water pumped in mode 4 could be used to irrigate fully a combination of corn and winter wheat at Garden City. Note that during part of the winter the water was not allocated because weather sometimes prohibits irrigation. A similar allocation procedure was followed for all modes at the three locations. Water was allocated for corn without preplant irrigation, for corn with preplant irrigation, and for corn in combination with winter wheat. The annual percentage of the capturable wind energy used for irrigation and the proportion of total energy derived from the wind were summarized.

Annual, capturable, wind energy use increases substantially in each mode with preplant irrigation (figs. 19-21). At Columbus, 43 to 47 percent of the wind energy would be used on fully irrigated corn compared with 22 percent without preplant irrigation in modes 2 and 4. Fully irrigated alfalfa uses water over a longer season than does corn, so would use 56

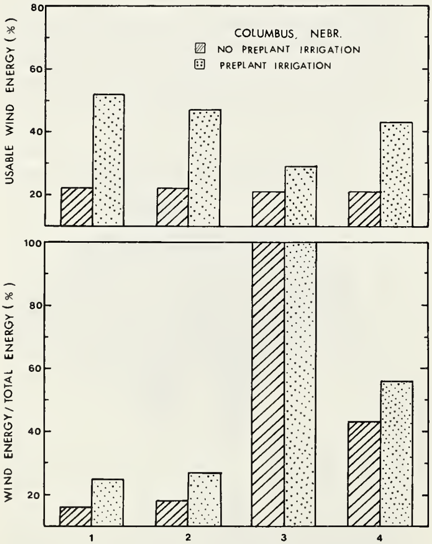


Figure 19.—Effects of preplant irrigation of corn on wind energy use by VAWT operated in four modes at Columbus, Nebr.

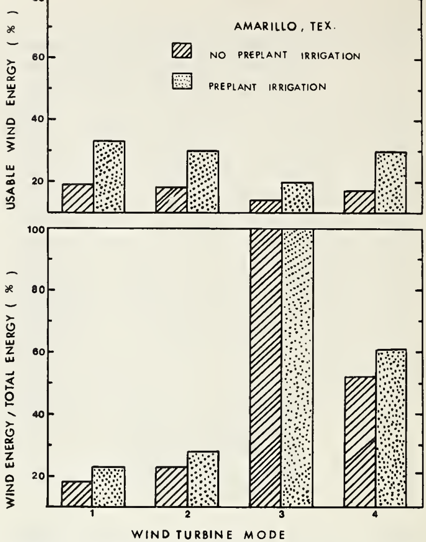


Figure 20.—Effects of preplant irrigation of corn on wind energy use by VAWT operated in four modes at Amarillo, Tex.

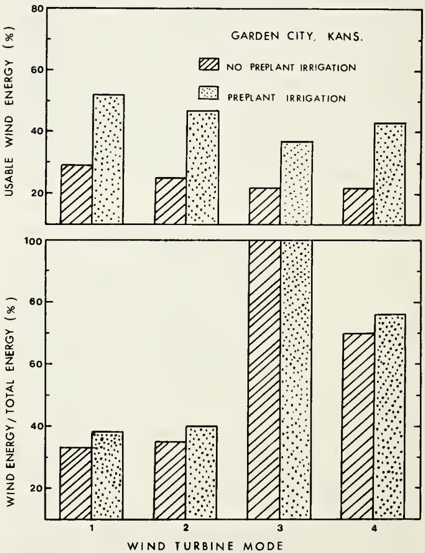


Figure 21.—Effects of preplant irrigation of corn on wind energy use by VAWT operated in four modes at Garden City, Kans.

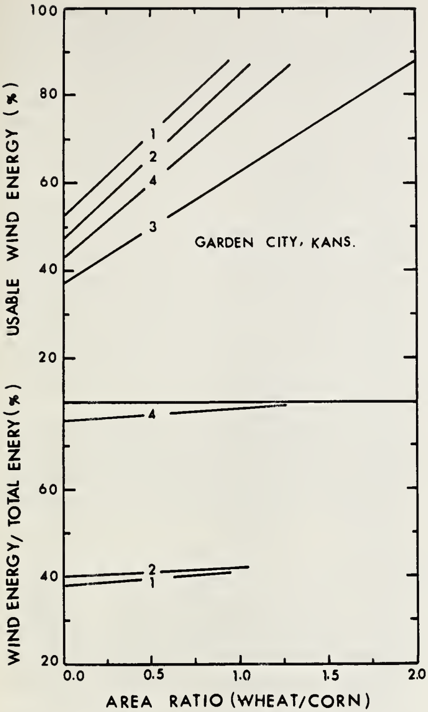


Figure 22.—Effects of mixing various ratios of corn and wheat on wind energy use by VAWT operated in four modes at Garden City, Kans.

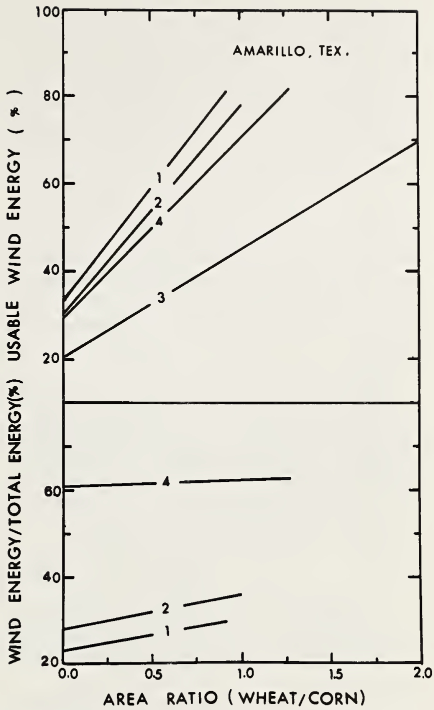


Figure 23.—Effects of mixing various ratios of corn and wheat on wind energy use by VAWT operated in four modes at Amarillo, Tex.

percent of the wind energy in the same modes.

Depending on mode, 20 to 33 percent of the wind energy at Amarillo and 38 to 52 percent at Garden City could be used on fully irrigated corn with preplant irrigation. Without preplant irrigation, generally less than 25 percent of the wind energy could be used.

Using auxiliary motors adds to system and fuel costs but has some advantages. Using motors in modes 1 and 2 (necessary for sprinklers) requires most auxiliary energy but also permits greatest percentage use of wind energy. This is because continuous operation in July and August produces maximum summer well yield and, thus, maximum area available for preplant irrigation per well.

Mode 4 requires only limited auxiliary energy but still uses a high percentage of the capturable wind energy. Though not investigated here, the large annual variations in precipitation and wind energy also dictate use of an auxiliary motor to insure acceptable yields in years with low wind energy. Conversely, the full potential of the wind turbine can be used in years with above-average wind energy.

The most effective way to use a large portion of the annual wind energy is to grow a mixture of crops that uses water in different seasons. For example, irrigating 1 ha of winter wheat for each hectare of corn permits 70 percent or more of the capturable wind energy to be used, except in mode 3 (wind power alone) where 2 ha of wheat are necessary (figs. 22, 23). In the South, if grain sorghum or cotton was substi-

tuted for corn, the amounts of capturable wind energy used would be slightly increased because their NIR is less than that of corn. Increasing the ratio of winter wheat to corn at Garden City or Amarillo would permit all the wind energy there to be used. Little irrigated winter wheat is grown in the Columbus area, so it was not considered there.

Limited irrigation is the practice of providing less water than the full NIR. Because crop water-use efficiency (WUE) is highest at less than full irrigation, farmers adopt limited irrigation whenever energy is expensive or water is limited. Because the Ogallala aquifer is being mined, extensive areas in the states south of Nebraska will have only enough water for limited irrigation by the year 2000 (*22*).

Limited irrigation works best on crops usually grown under dryland conditions in an area. For example, Stone (*24*) reported 3-year-average sorghum yields of 5,221, 5,912, and 6,353 kg/ha (83, 94, and 101 bu/A) for preplant, preplant plus one summer irrigation, and full irrigation, respectively, in southwestern Kansas. He concluded preplant plus one summer irrigation should be used to obtain high yields and highest WUE. He also noted that timing of the summer irrigation was not critical and that yields were acceptable with only a preplant irrigation. Thus, in western Kansas, limited irrigation of grain sorghum could use all the capturable wind energy whenever weather permitted irrigation.

In Texas, Musick and Dušek (*15*) found a preplant irrigation and a single 10-cm irrigation applied to grain sorghum at heading-to-milk stage gave high WUE and good yields. In this case, 58 and 52 percent of the annual capturable wind energy in modes 2 and 4, respectively, could be used. It is also possible to reduce the summer irrigation below 10 cm, with some yield reduction, and further increase annual wind energy use.

Winter wheat, too, responds well to limited irrigation. Fall preplant irrigation of winter wheat at Garden City averaged 3,033 kg/ha compared with 3,309 kg/ha for full irrigation in a 5-year study (*7*).

CONCLUSIONS

We investigated the application of dedicated wind turbine systems without energy storage to irrigation pumping in the Great Plains and concluded:

1. Sprinkler irrigation requires a relatively constant flow mode, and about 45 percent of the irrigation energy demand is in this mode —25 percent to power the sprinklers and 20 percent to lift water for the sprinklers. A wind turbine coupled with a variable-ratio transmission and auxiliary motor sized to equal the rated power of the wind turbine (mode 2) can supply 30 to 45 percent of the sprinkler energy demand from wind power, depending on crop and location.

2. About 55 percent of the energy demand is for lifting water for surface distribution systems. By using small reservoirs or irrigation canals for temporary storage, surface distribution systems can be supplied by variable flow pumping. A wind turbine with variable-ratio transmission and auxiliary motor, sized at 0.4 the rated power of the wind turbine (mode 4), can supply 60 to 70 percent of this demand from wind power.

3. From the preceding results, we concluded that wind turbine systems in modes 2 and 4 could supply half or more of the energy demand of Great Plains irrigation using the present mix of sprinkler and surface distribution systems.

4. Comparison of four wind turbine operational modes showed 2 and 4 were superior. The variable-ratio transmissions used in modes 2 and 4 increased the capturable wind energy by 10 to 25 percent compared with the fixed-ratio transmissions of modes 1 and 3.

5. Using an auxiliary motor with a wind turbine requires fossil fuels and increases capital costs but also has some advantages. Motors increase well yields in summer and, thus, increase area that can be preplant irrigated with the wind turbine in other seasons. This resulted in a 10 to 20 percent increase in the annual wind energy used on summer irrigated crops compared with use by the wind-alone system (mode 3).

6. The computer program (Appendix C) developed in this study can be used to determine needed wind turbine size for given well and aquifer characteristics. Simulation of performance of a typical well showed that for a

wind turbine operated in modes 3 and 4, two wells were required to yield as much water as that produced by a continuously pumped well. Maximum permissible flow rates through the well-screen limit maximum well yield under cyclic pumping. At 60 percent drawdown, inflow rates were 23 to 33 percent greater with cyclic than with continuous pumping.

7. Adopting various irrigation management practices increases the use of annual, capturable wind energy. In modes 2 and 4, fully irrigated corn with preplant irrigation used about 30 percent of the annual wind energy at Amarillo and 45 percent at Columbus and Garden City. Less than 25 percent was used without preplant irrigation. Fully irrigating equal areas of corn and winter wheat used 70 to 85 percent of the annual wind energy, depending on location. Substituting grain sorghum, or cotton in the South, for corn permits slightly higher use of annual wind energy. Fully irrigated alfalfa in eastern Nebraska used 56 percent of the annual wind energy. Thus, fully irrigated summer crops with preplant irrigation will use 30 to 60 percent of the capturable wind energy, depending on crop and location.

8. When available water is limited or energy is expensive, relative to returns, farmers often limit irrigation of crops adapted to dryland farming. With limited irrigation, 50 to 100 percent of the annual wind energy can be used, depending on crops and management practices.

LITERATURE CITED

(*1*) Anschutz, John A., and Ralph Lipper. 1975. Summary of electrical irrigation pumping loads in Kansas. *In* Report of 50th Annual Meeting, Kansas Committee on the Relation of Electricity to Agriculture, 1974-75, Agricultural Engineering Department, Kansas State University, Manhattan.

(*2*) Apt, Kenneth E. 1976. Applicability of the Weibull distribution function to atmospheric radioactivity data. Atmospheric Environment 10(9):777-782.

(*3*) Blackwell, Ben F., Robert E. Sheldahl, and Louis V. Feltz. 1976. Wind tunnel performance data for the Darrieus wind turbine with 0012 blades. Report No. Sand 76-0130, Sandia Laboratories, Albuquerque, New Mex., 61 p.

(*4*) Elliot, Dennis L. 1977. Synthesis of national wind assessments. *In* Annual Report of the Wind Characteristics Program Element for April 1976 through June 1977. Battelle Pacific Northwest Laboratories report No. BNWL-Wind-10, Richland, Wash., p. 104-106.

(*5*) Geraghty, James J., David W. Miller, Frits Van Der Leeden, and Fred L. Troise. 1973. Water atlas of the United States. Water Information Center, Inc., Water Research Bldg., Manhasset Isle, Port Washington, New York.

(*6*) Gilmore, Earl, Robert E. Barieau, and Vaughn Nelson. 1977. Feasibility of using wind power to pump irrigation water. Report No. 77-101 prepared for Governor's Energy Advisory Council, Austin, Tex., 58 p.

(*7*) Grimes, Donald W., George M. Herron, and Jack T. Musick. 1962. Irrigation and fertilizing winter wheat in southwestern Kansas. Kansas Agricultural Experiment Station Bulletin 442, Manhattan.

(*8*) Hantush, Mahdi S. 1964. Hydraulics of wells. *In* Advances in Hydroscience, Ven Te Chow, editor, 1:282-430. Academic Press, New York, 442 p.

(*9*) Irrigation Journal. 1977. Survey issue, November-December 1977. Brantwood Publications, Inc., Elm Grove, Wis.

(*10*) Jacob, Charles E. 1947. Drawdown test to determine effective radius of artesian wells. Transactions of the American Society of Civil Engineers 112:1047-1070.

(*11*) Justus, Carl G., W. R. Hargraves, and Amir Mikhail. 1976. Reference windspeed distributions and height profiles for wind turbine design and performance evaluation applications. Technical Report for ERDA Division of Solar Energy under Contract No. E(40-1)-5108, Georgia Institute of Technology, Atlanta.

(*12*) Karassik, Igor J., William C. Krutzsch, Warren H. Fraser, and Joseph P. Messina, editors. 1976. Pump handbook. McGraw-Hill Book Co., New York.

(*13*) McDaniels, Louis L. 1960. Consumptive use of water by major crops in Texas. Bulletin 6019, Texas Board of Water Engineers, Austin.

(*14*) McWhorter, David B., and Daniel K. Sunada. 1977. Ground-water hydrology and hydraulics. Water Resources Publication. P. O. Box 303, Fort Collins, Colo., 290 p.

(*15*) Musick, Jack T., and Donald A. Dusek. 1971. Grain sorghum response to number, timing, and size of irrigations in the Southern High Plains. Transactions of the American Society of Agricultural Engineers 14(3):401-404, 410.

(*16*) New, Leon. 1975. 1974 High Plains irrigation survey. Texas Agricultural Extension Service Report, Texas A&M University, College Station, 23 p.

(*17*) Reed, Jack W. 1975. Wind power climatology of the United States. Report No. Sand 74-0348, Sandia Laboratories, Albuquerque, New Mex.

(*18*) Reinke, John W., and David L. Kill. 1970. Modern design techniques for efficient high-capacity irrigation wells. American Society of Agricultural Engineers Paper No. 70-732, presented at 1970 winter meeting of American Society of Agricultural Engineers, Chicago, Ill.

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(*19*) Rorabaugh, M. I. 1953. Graphical and theoretical analysis of step-drawdown test of artesian wells. Transactions of the American Society of Civil Engineers 79:362.

(*20*) Sloggett, Gordon. 1976. Energy used for pumping irrigation water in the U.S., 1974. Proceedings of Conference on Energy in Agriculture, Washington University, St. Louis, Mo., June 17.

(*21*) ______ 1976. Energy and U.S. agriculture irrigation pumping, 1974. U.S. Department of Agriculture, Economic Research Service, Agricultural Economics Report No. 376, 39 p.

(*22*) Solomon, Bekury. 1971. An economic analysis of intertemporal allocation of groundwater in the central Ogallala formation. Unpublished Ph.D. dissertation, Oklahoma State University, Stillwater.

(*23*) Stepanoff, Alexey J. 1957. Centrifugal and axial flow pumps. John Wiley and Sons, Inc., New York, 462 p.

(*24*) Stone, Loyd R. 1978. Maximizing yield benefits when using limited amounts of irrigation water. Proceedings of Irrigation Workshop. Cooperative Extension Service, Kansas State University, Manhattan. February 22-23.

(*25*) Strikland, John H. 1975. The Darrieus turbine: a performance prediction model using multiple streamtubes. Report No. Sand 75-0431, Sandia Laboratories, Albuquerque, New Mex.

(*26*) U.S. Department of Agriculture, Soil Conservation Service. 1972. Irrigation guide for Nebraska, 1972. Lincoln.

(*27*) ______ Soil Conservation Service. 1975. Kansas irrigation guide, 1975. Lincoln, Nebr.

GPO 824–534